EXCAVATION SUPPORT SYSTEM WITH PILES – CASE STUDY

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Summary: *Limited space for the construction of facilities requires the design of underground garages, which requires excavation support system design. The support system for deep excavations can be designed with piles. This type of excavation support system requires adequate geological research, definition of soil-pile interaction and adoption of an appropriate calculation model. The paper presents a case study of the design of excavation support system with piles for the construction of an underground three-story garage in Kruševac.*

Keywords: *Excavation support system, piles, wales and struts, calculation model.*

1. INTRODUCTION

Growing urbanization of the cities results in the construction of a large number of facilities. Since the construction space is limited, the vehicle parking space is reduced. That is the reason why the designers more often decide to design the underground floors for the purpose of vehicle parking. It happens very often that the construction of a wide excavation for the underground floor construction is not possible, therefore, it is necessary to design the excavation support systems which will secure the vertical excavation walls. Construction of excavation support walls in segments can be justified in the cases where there is one underground floor of usual floor height. In the cases where the depth of the excavation is considerably bigger RC diaphragm or the curtain wall of piles as an excavation support system can be applied. Piles and diaphragms can be designed as cantilever structures. However, it is justified only when the depth of the excavation is up to 7 m [1]. With an increase of the excavation depth, the necessary depth of setting-up the diaphragms or the piles in the ground under the excavation increases as well. Therefore, there is a necessity for designing the excavation support system with wales and struts. Hot formed I-shaped steel profiles are used for wales and struts support system design. The paper presents the case study of the excavating support system design for the construction

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of the underground garage that consists of three underground floors 3.15 m height and which base dimensions are 92 x 35 m.

2. DESCRIPTION OF THE CONSTRUCTION OF THE EXCAVATION SUPPORT SYSTEM

The construction of the vertical excavation support system is designed using the drilled CFA piles (Continuous Flight Auger System). Technology of the piles constructed with the application of the continuous spiral was developed in Great Britain in the second half of the XIX century and it has become widely used in our country since the beginning of the XX century. The production of the CFA piles is characterized by high productivity, relatively low price, low noise and vibration level which enable them to be constructed in all types of soil. The production of the piles has three phases (Figure 1) [2]:

1. Drilling with the support of the pipe with the spiral- auger until reaching the designed depth. It is not necessary to support the side of the excavation using the pipe or the bentonite suspension because the stability of the excavation is supported by a rotating auger. This way of drilling is faster and more economical than other methods.
2. After reaching the necessary depth, auger is raised 30-40 cm and the process of concreting begins. The process takes place when the concrete pump is connected to the upper part of the spiral pipe, then the plug at the lower end opens and the concrete fills in the drill hole. During the concreting the spiral is pulling out with or without rotation.
3. When the drill hole is filled in with the concrete the prepared armature basket is brought. It can be set with or without vibrations.

One part of the soil is pulling out while the spiral is pulling back (with the rotation) during the process of drilling and the other part is compressed into the surrounding soil. That is the way the soil in the immediate proximity of the piles is more compressed which leads to greater load capacity of piles. Besides that, the amount of the soil which should be transported is smaller [2].

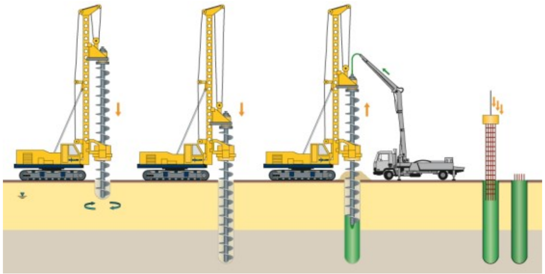


Figure 1. The phases of the construction of CFA piles [2]

In this case study the diameter of the piles is 800 mm and their length is 12.5 m, 14.2 m and 18 m. Length of the piles is conditioned by the funding depth of the neighboring objects and the construction of the newly designed garage with the grade separated floors.

Setting-up depth of the piles in the ground under the excavation level is 6.25 m in the axis 9, up to 8 m in the axis 2. Figure 2 shows the layout, where the phases of the construction of the foundation plate and wales and struts are presented, while Figure 3 and 4 show the characteristic longitudinal and transversal section with the excavation phases. Excavation and the excavation support system are designed in eleven phases:

- I PHASE: Removing the objects and furniture from the location and mechanical excavation of the surface soil layer to the depth of -4.20 m to -5.90 m (wide excavation). Stabilization of the slope is carried out by setting the geotextile, reinforcing mesh, wire mesh and torcrete of minimal thickness of 8 cm. After which the working plateau is formed by flattening and leveling, with the necessary compaction of soil in order to avoid unwanted soil deformation during the piles setting. During this phase the piles Ø800 mm are constructed along the object edge (Figure 2). Five groups of four piles have been foreseen, outside of the primary excavation support system over which a head plate is set, which is connected to the head beam of the primary excavation support system. The aim of these piles is to like counterfort, with the activation of the soil surrounding them, provide less displacements of the primary construction for the excavation support system.
- II PHASE: After constructing the piles, the head beams with dimensions of 100x100 cm, 80x100 cm and 150x100 cm are constructed in the whole scope of the constructed piles, as well as the construction of the head plate 50 cm thick over the five groups of four piles.
- III PHASE: In order to prevent the impact of the underground water on the construction pit, lowering the level of the underground water has been designed constructing the drilled well around the construction pit and constantly pulling the water out from them. The drenches, leveled with the head beams are designed for the drainage of the atmospheric water.
- IV PHASE: Excavation of the ground between axes D to E to the elevation of foundation with the formation of slope in order to prevent material grinding. After the excavation the subsoil and part of the foundation plate are constructed. In this phase the observation of the displacements of the head beams is necessary. If the displacements are larger than 3 cm horizontally, there is a necessity for wales and struts, which are used to support the piles from the constructed foundation plate.
- V PHASE: Soil excavation between axes G to H to the elevation of foundation with the formation of the slope in order to prevent material grinding. Displacement measurements of the head beams are conducted and, in the case, when the displacement is larger than 3 cm wales and struts are constructed.
- VI PHASE: Forming the ramp for the removal of the excavated material. The ramp is designed between the axes H to N and 3 to 9. While forming the ramp it is necessary to construct wales and struts in the level of the head beams and in the level of -6.60 m between the axes I to J and 2 to 4.
- VII PHASE: Construction of wales and struts in the level of head beams between axes A and C with the aim of preventing the displacement of the excavation support system.
- VIII PHASE: The excavation between the axes A to C and 1 to 6. Construction of the part of the foundation plate. Placing wales and struts in the corner between the axes A to C, as well as between axes 5 to 9 in the level of -6.60 m. The piles are supported with the slanted struts from the foundation plate between the axes 5 to 7.
- IX PHASE: Excavation of the soil to the designed level between the axes 5 to 9 and A

to D, after which the foundation plate is constructed.

- X PHASE: Excavation of the part of the soil material which was left over between the axes E to G and the construction of the foundation plate at that particular part.
- XI PHASE: Construction of wales and struts at the level of the head beams between the axes J to N and axes 6 to 9. Excavation of the soil ramp to the level of -8.30 m, after which the wales and struts are set at that level. When the support is set, the rest part of the soil material is excavated and the last segment of the foundation plate of the garage is constructed.

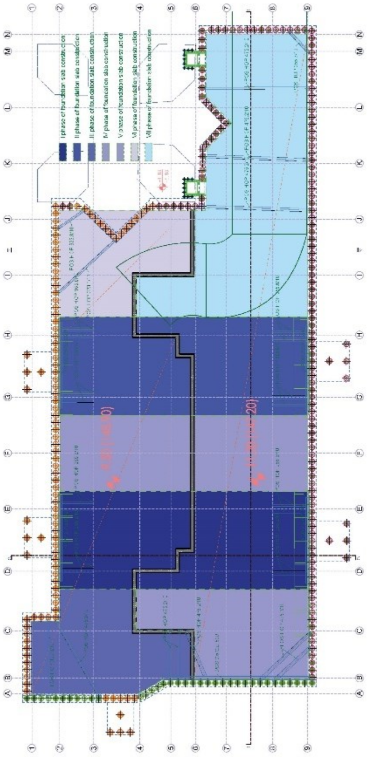


Figure 2. Phases of the foundation plate construction

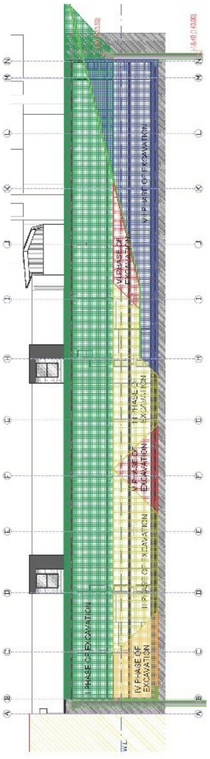


Figure 3. Characteristic longitudinal section

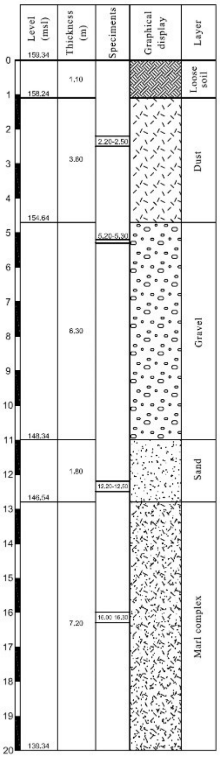


Figure 5. Lithological members of soil

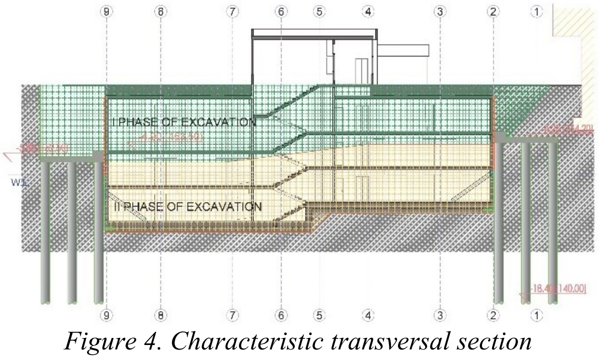


Figure 4. Characteristic transversal section

3. CALCULATION MODEL OF THE CONSTRUCTION OF THE EXCAVATION SUPPORT SYSTEM

Calculation and design of the excavation support system has been conducted in the software package *Radimpex Tower 8.2*. Piles, head beams and wales and struts are modeled with beam finite elements, while the head plates are modeled with the surface finite elements. The suitable geometrical characteristics of the elements were defined in calculation model, while the materials are treated as linear elastic. Concrete elements are designed from the concrete type MB30 (C25/30) and the steel elements are made of steel S235. Interaction between piles and soil is modeled with the linear support, where the stiffness of the support matches the horizontal module of the soil reaction. Linear support prevents the displacement in the horizontal directions in the part of the piles set in the soil under the excavation level. Above the excavation level the piles penetration into the surrounding soil has been prevented with the nonlinear linear support, which prevents the displacement of the piles perpendicular to the curtain wall of piles towards the soil. The displacement of the piles in the vertical direction has been prevented with the proper supports in the base of the piles.
Geomechanical research with five drillholes has been conducted, with the aim of defining the characteristics of the soil. It has been determined that the terrain consists of five lithological members (Figure 5):

- Loose soil - surface part of the terrain with approximate thickness of 1.10 m, which is a combination of gravel, sand and dust. It is not of great importance for the design of the excavation support system, because it has to be completely removed before the construction begins,
- Dust - a hard layer of dust and clay, 3.60 m thick,
- Gravel - gravel mixed with dust material of diverse mineral composition, well compacted, 6.3 m thick,
- Sand - hard density and well compacted, 1.80 m thick,
- Marl complex - dusty material, with the presence of clay and sand, well compacted layer, incompressible.

For defining the horizontal module of the soil reaction the expression according to Vesić is applied [3]:

$$k_h = \frac{0.65}{D} \cdot \sqrt[12]{\frac{E_s D^4}{E_p I_p}} \cdot \frac{E_s}{1-\mu_s^2} \tag{1}$$

where is:
D – pile diameter,
E_s, μ_s –elasticity module and Poisson's ratio of soil,
E_p, I_p –elasticity module and moment of inertia of a pile,

Elasticity module of each layer of soil is defined based on the compression module (M_v) determined by the oedometer test, according to the relation [4]:

$$E_s = \frac{(1-2\mu_s)\cdot(1+\mu_s)}{1-\mu_s}\cdot M_v \qquad (2)$$

where Poisson's ratio 0.30 has been adopted [5].

Calculated values of the horizontal module of the soil reaction by applying the relations (1) and (2) are shown in Table 1.

Table 1. Horizontal module of the soil reaction

Depth [m]	M_s [kPa]	E_s [kPa]	k_h [kN/m^3]
1.10 ÷ 4.70	4 600.00	3 417.14	1 832.92
4.70 ÷ 11.00	10 000.00	7 428.57	4 250.98
11.00 ÷ 12.80	10 000.00	7 428.57	4 250.98
> 12.80	13 000.00	9 657.14	5 648.43

The piles are loaded by active soil pressure [6]:

$$p_a = \gamma\cdot h\cdot k_a - 2c\sqrt{k_a} + p_0\cdot k_a, \quad k_a = tg^2(45-\varphi/2) \qquad (3)$$

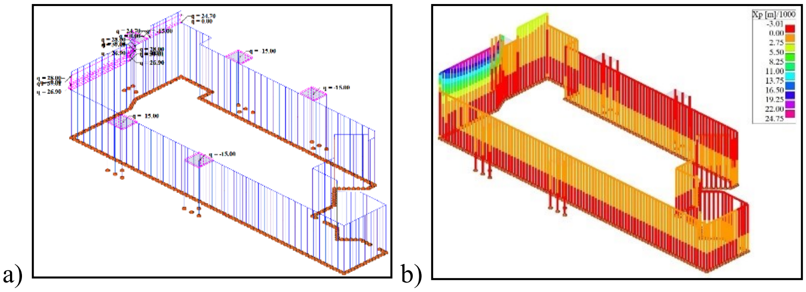
Specific weight (γ), the angle of the internal friction (φ) and cohesion are determined by the appropriate laboratory experiments. In the calculation of the load the angle of the internal friction and cohesion were divided by the safety factor 1.30 (Table 2).

Table 2. Physical and mechanical characteristics of the soil

Layer	γ [kN/m^3]	φ	c [kN/m^3]	φ_m	c_m [kN/m^3]
Dust	21.00	38.00	0	29.23	0.00
Gravel	20.00	32.00	5.00	24.62	3.85
Sand	21.00	29.00	15.00	22.31	11.54

Load p_0 includes the impact of the neighboring objects on the excavation support system. The impact of the underground water on the excavation support system has not been covered by the analysis, because lowering the level of the underground water under the excavation level has been foreseen.

For the control of the stress-strain state of the support four spatial FEM models have been made, where phases of the excavation are mathematically described. The first model corresponds to the excavation phases I to III, where the load capacity and the size of piles displacements in the axes A and B are controlled, which accept the soil load and neighboring objects as a console girder, without the application of the wales and struts (Figure 6a). Displacements of the top of the piles are 24.75 mm (Figure 6b). The second calculation model covers phases IV and V of the excavation construction. Figure 7a shows the geometry of the model with the loads, while Figure 7b shows the geometry of the model with the wales and struts supporting piles from the previously constructed counter plate. The calculation of the model without wales and struts has showed that the horizontal displacements are 24.66 mm and 20.40 mm (Figure 7c) and are smaller than 60 mm, which has been set as allowed displacement in the design. The design has foreseen the observation of the deformation of the support structure during the construction and the wales and struts have as well been foreseen in the case when the displacement of the construction is significantly larger than the calculated displacements. Setting the wales and struts in axes 2 and 9, the displacements are lowering in y horizontal directions of the global coordinate system to 12.69 mm (Figure 7d). The third calculation model covers phases VI to X of the excavation construction. Geometry, load and displacements in the horizontal direction are showed in Figure 8. Displacements in the horizontal directions are significant (48.37 mm in x direction and 56.61 mm in y direction). Piles, wales and struts in the axis 1 are designed with the aim that displacement of the curtain wall finds the place within the boundaries of the allowed displacement, while the significant displacements in the y direction are controlled by adding wales and struts in axis 6 and 9 in the last excavation phase. Finally, with the last calculation model stress-strain analysis is conducted for the excavation support system when the entire soil is excavated. Geometry and loads have been showed in Figure 9a, while the sizes of the displacements in the horizontal directions are showed in Figure 9b. Displacements in the x direction of the global coordinate system are nearly the same as in the previous phase, while the additional wales and struts are lowering displacements in the y direction to 37.63 mm. It should be emphasized that without groups of four piles connected by head plates to head beams as counterfort, displacements in y direction would be 51.13 mm, which is around 36 % larger than in the case with counterfort. This means that there would be necessary to add more wales and struts in case without counterforts to reduce displacements, but with the presence of wales and struts the excavation of soil would be more difficult. This is the advantage of the design of counterfort piles.



a) b)

Figure 6. Calculation FEM model – I to III phase of excavation construction: a) geometry and loads; b) displacements in x direction of global coordinate system

In each calculation phase RC structural elements are designed according to the theory of limit states. The stress and stability control of steel structure elements have been conducted by applying the permissible stress theory. Soil load is treated as exceptional load, because the construction is temporary, therefore, based on that the partial safety factor for loads 1.30 has been adopted for designing the concrete structural elements. The safety factor for defining the allowed stress of the steel material 1.20 has been adopted as well. Based on the RC element design, the piles reinforcement bar has been adopted as 14BØ20, 14BØ22, 14BØ25 and 14BØ28, while head beams are reinforced with 6BØ20, 6BØ22 and 6BØ28, depending on the stress state in the structural elements. Conducting the stress control and steel elements stability, the assumed dimensions of the struts are confirmed (Ø323.8x10, Ø355.6x10 and Ø457.2x10) as well as wales dimensions (2HEA320 and 2HEA500).

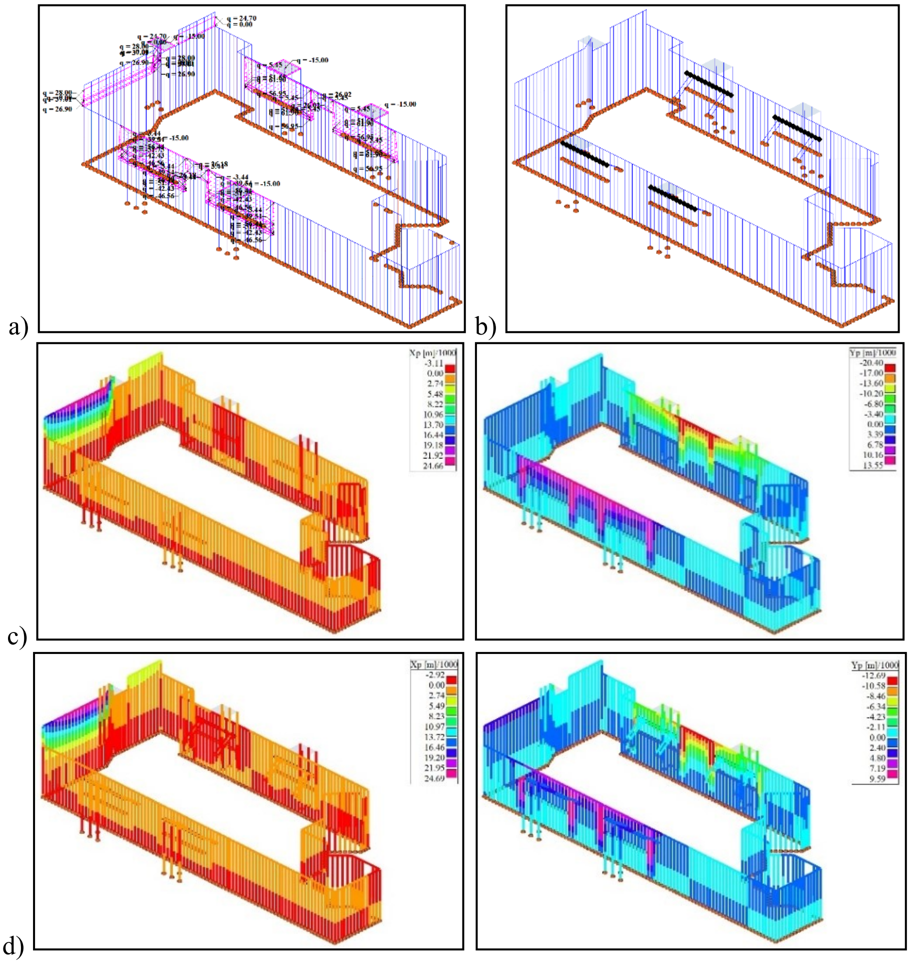


Figure 7. Calculation FEM model – IV and V phase of excavation construction: a) geometry and loads; b) geometry with wales and struts; c) displacements in x and y direction of global coordinate system of model without wales and struts; d) displacements in x and y direction of global coordinate system of model with wales and struts

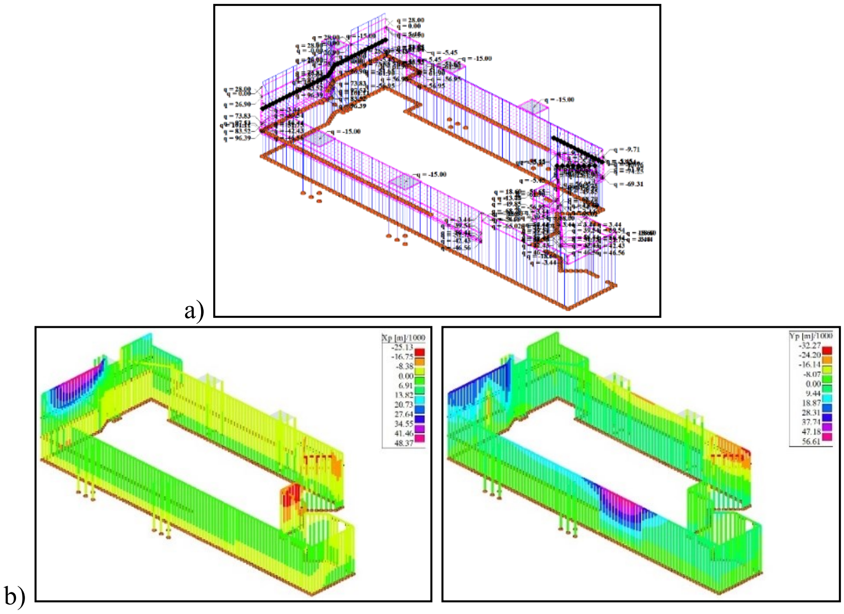


Figure 8. Calculation FEM model – VI do X phase of excavation construction: a) geometry and loads; b) displacements in x and y direction of global coordinate system

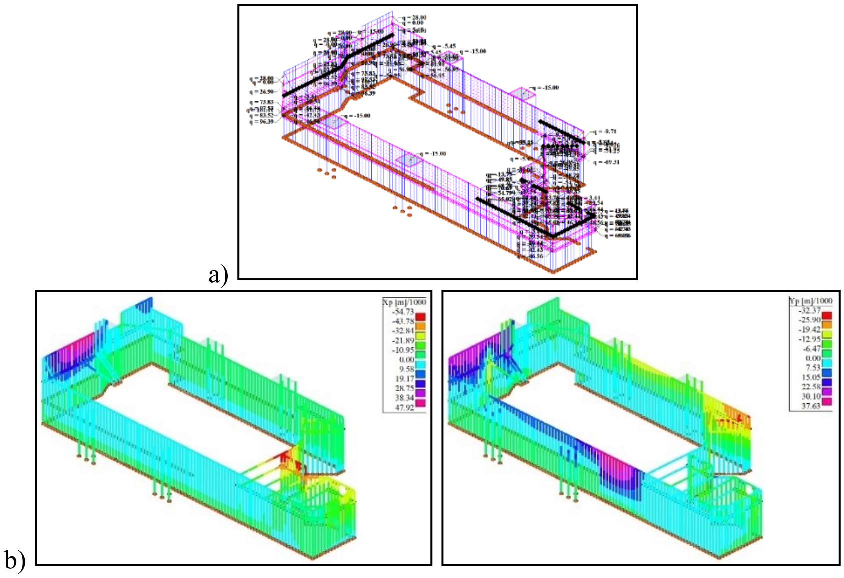


Figure 9. Calculation FEM model – XI phase of excavation construction: a) geometry and loads; b) displacements in x and y direction of global coordinate system

4. CONCLUSION

The paper presents the case study of designing the excavation support system for constructing the three-floor underground garage in Kruševac. Taking into account the depth of the excavation, the excavation support system is designed as the curtain wall of piles. Designing the piles as a console is not rational because it requires deep nailing of the piles into the soil under the level of the excavation. That is the reason for designing the wales and struts, which lowers the depth of the piles setting, as well as the displacements of the top of the excavation support structure. In order to reduce number of wales and struts the groups of piles can be designed as counterforts. This is the manner in which the excavation of the soil is easier than in the case with more wales and struts, while displacements in horizontal directions are kept in the range of allowed displacements. Excavation construction is designed in phases. Therefore, it is necessary to take care of the load capacity and stability of the support construction in each phase, as well as of possibility of removing the soil from the construction site. In order to define the adequate parameters of the interaction of the piles and soil and active pressures of soil to the support structure, it is necessary to conduct the quality geomechanics researches. Geomechanics researches cover the terrain examination and laboratory tests with the aim of defining more precise physical and mechanic characteristic of all lithological layers which participate in the soil of the subject location. Those parameters represent the input data for forming the adequate calculation model of the support structure. The calculation models should cover all phases of the excavation construction, since the relevant effects of actions in some elements of the excavation support system can appear in different phases. Next to the load capacity criteria, the displacement criteria of the excavation support system are reliable as well, especially while designing the position and dimensions of the wales and struts and counterforts. The detailed explanation of the design phases and calculation of the excavation support system presented in this paper can be used as a useful instruction for the engineers in everyday practice.

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ОБЕЗБЕЂЕЊЕ ИСКОПА ШИПОВИМА – СТУДИЈА СЛУЧАЈА

Резиме: *Ограничен простор за изградњу објеката условљава пројектовање подземних гаража, а што захтева обезбеђење ископа. Обезбеђење дубоких ископа се може извести подградом од шипова. Овакав вид обезбеђења ископа захтева адекватна геолошка истраживања, дефинисање интеракције тла и шипа и усвајање одговарајућег прорачунског модела. У раду је приказана студија случаја пројектовања обезбеђења ископа шиповима за извођење подземне гараже у три нивоа у Крушевцу.*

Кључне речи: *Обезбеђење ископа, шипови, разупирање, прорачунски модел*